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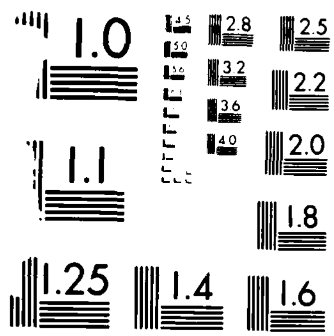

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THE ROLES OF $\vec{V}\times\vec{B}$ AND DENSITY GRADIENTS IN PLASMA ELECTRIC FIELDS MEASURED FROM THE SHUTTLE ORBITER

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Hanscom Air Force Base, MA 01731

"This technical report has been reviewed and is approved for publication"

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Plasma electric fields due to motion through the geomagnetic field and to density gradients are of the same order of magnitude in the wake of shuttle sized objects. Density gradient fields dominate in the wakes of smaller satellites while $\vec{V}\times\vec{B}$ fields dominate behind larger structures. Supporting experimental data is cited. Computational results (calculated using the spacecraft charging code POLAR) which demonstrate the roles of the two fields in the wake are also presented.

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THE ROLES OF $\vec{V} \times \vec{B}$ AND DENSITY GRADIENTS IN PLASMA ELECTRIC FIELDS MEASURED FROM THE SHUTTLE ORBITER

The electric fields observed on satellites can be due to a number of environmental influences. Density gradients and $\vec{v} \times \vec{B}$ are two causes of electric fields measured in low earth orbit. The electric fields due to density gradients affect mainly the smaller satellites while voltages generated by moving through magnetic fields are dominant on larger objects. For spacecraft the size of Space Shuttle Orbiter (10-30 m) the two effects are of the same order of magnitude. Measurements made during flights of the orbiter support this observation.

When a good conductor moves across magnetic field lines it develops a tangential electric field to cancel the Lorentz force on its conduction electrons. The tangential electric field can be found in the plasma's frame of reference by solving

$$\vec{F}_L = e(\vec{E} + \vec{v} \times \vec{B}) = 0$$

to find

$$\vec{E} = -\vec{v} \times \vec{B} \tag{1}$$

An electric field is also generated by the density gradient found in the wake of a fast moving spacecraft moving through a dense plasma. By fast we mean that the spacecraft is supersonic with respect to the dominant ion species, and by dense we mean that spacecraft dimensions are large compared with the unperturbed ionospheric plasma Debye length. The shuttle orbiter satisfies both these conditions. The potential in the wake can be estimated using quasineutrality and the Boltzmann relation for electrons.

$$n_i \simeq n_e$$

$$n_e = n_o\, e^{(\phi/\theta_e)}$$

where $n_e(n_i)$ is the local density of electrons (ions), n_o is the undisturbed density, θ_e is the temperature of the electrons in eV, and ϕ is the local potential. Solving for ϕ

$$\phi = \theta_e \,\ell n\left(\frac{n_e}{n_o}\right)$$

The electric field resulting from density gradients can be approximated by the change in the local potential over a length roughly the size of the cross-section of spacecraft with respect to the ram direction. Or

$$|\vec{E}| \simeq -\frac{\Delta\phi}{L} \simeq -\frac{\theta}{L}\left(\ell n\left(\frac{n_2}{n_o}\right) - \ell n\left(\frac{n_1}{n_o}\right)\right) \tag{2}$$

where n_1 and n_2 are two local densities.

The magnitude of electric fields due to the two effects can be approximated using Eqs. (1) and (2). Assuming a 10^{11} m^{-3} plasma with a magnetic field of 0.4 gauss and a density gradient of four orders of magnitude in the wake (as observed on the shuttle orbiter by Murphy et al.)[1] we can estimate the magnitude of the electric fields caused by both processes. Using an orbital velocity of 7.7 km/sec, the $\vec{v} \times \vec{B}$ field would be 0.31 V/m and independent of vehicle dimensions. Table 1 is for density gradient fields and, as can be seen from Eq. (2), depends inversely on the size of the orbiting spacecraft.

Table 1. Electric Fields Due to Density Gradients of Four Orders of Magnitude (as observed by Murphy *et al.*)[1]

θ = 0.1 eV		θ = 0.2 eV	
L (m)	E (V/m)	L (m)	E (V/m)
0.5	1.8	0.5	3.7
5.0	0.18	5.0	0.37
50.0	0.018	50.0	0.037

The electric field magnitudes lead one to expect small satellites (~1-2 meters in diameter) to have local fields dominated by density gradient fields and large spacecraft (~50-200 meters, i.e., space stations) to have fields mainly dependent on magnetic field effects. Objects the size of the space shuttle (~10-30 m) will experience electric field contributions of the same order of magnitude from both the Lorentz force and the density gradient fields.

Small satellites have observed electric fields of the order of 1 V/m. Samir *et al.*[2] measured these plasma potentials as their probe rotated through the wake of the Atmospheric Explorer - C (AE-C). Measurements made on Orbiter flights have indeed seen electric fields from both influences. Raitt *et al.*[3] recorded $\vec{v} \times \vec{B} \cdot \vec{\ell}$ on the order of the predicted magnitude, where $\vec{\ell}$ was the distance from the detector to spacecraft ground (the engine nozzle). The potentials they observed correspond to a maximum electric field of roughly 0.4 V/m. Smiddy *et al.*[4] measured a density gradient electric field of 0.16 V/m while moving with the detector aligned with the velocity vector.

Computer calculations performed at S-CUBED in cooperation with the Air Force Geophysics Laboratory (AFGL) using the POLAR code (Cooke _et al._)[5] also show the interaction of the two electric fields. Solutions of the space potentials were calculated self-consistently along with current balance of the ambient plasma to the test objects. An object Mach vector of $-8\hat{z}$ through a 0.1 eV plasma at densities of 1 m^{-3} and 10^{12} m^{-3} containing a magnetic field of 0.4 gauss in the $-\hat{x}$ direction was used. Figure 1 is a picture of the 8 x 8 x 2 meter plate used to generate Figures 2 and 3 and Figure 4 is the 6 x 16 x 2 meter box used in Figures 5 and 6.

The magnetic field generated an electric field of -0.25 V/m along the y-axis. The density gradient generated electric field was found by the code (Katz _et al._)[6]. Figure 2(a) shows the potential around the plate due only to $\vec{v} \times \vec{B}$ field in plasma's reference frame. Figure 2(b) is the same set of potentials as seen in the spacecraft frame. Figures 3(a) and 3(b) are of the same object in the two reference frames with the density gradient electric fields included. In Figure 3(b), the electric fields interact in the wake in an anticipated manner. Note that the $\vec{v} \times \vec{B}$ field is not perturbed by density gradient fields in the ram direction since the ion density there is almost undisturbed and thus there is no quasineutral electric field. Figures 5 and 6 are of a metal box the size of the shuttle cargo bay under the same circumstances.

In conclusion, for shuttle sized objects care must be taken when interpreting measurements of plasma electric fields or space potentials. Plasma parameters, geometrical effects, and velocity effects may obscure the source of observed electric fields.

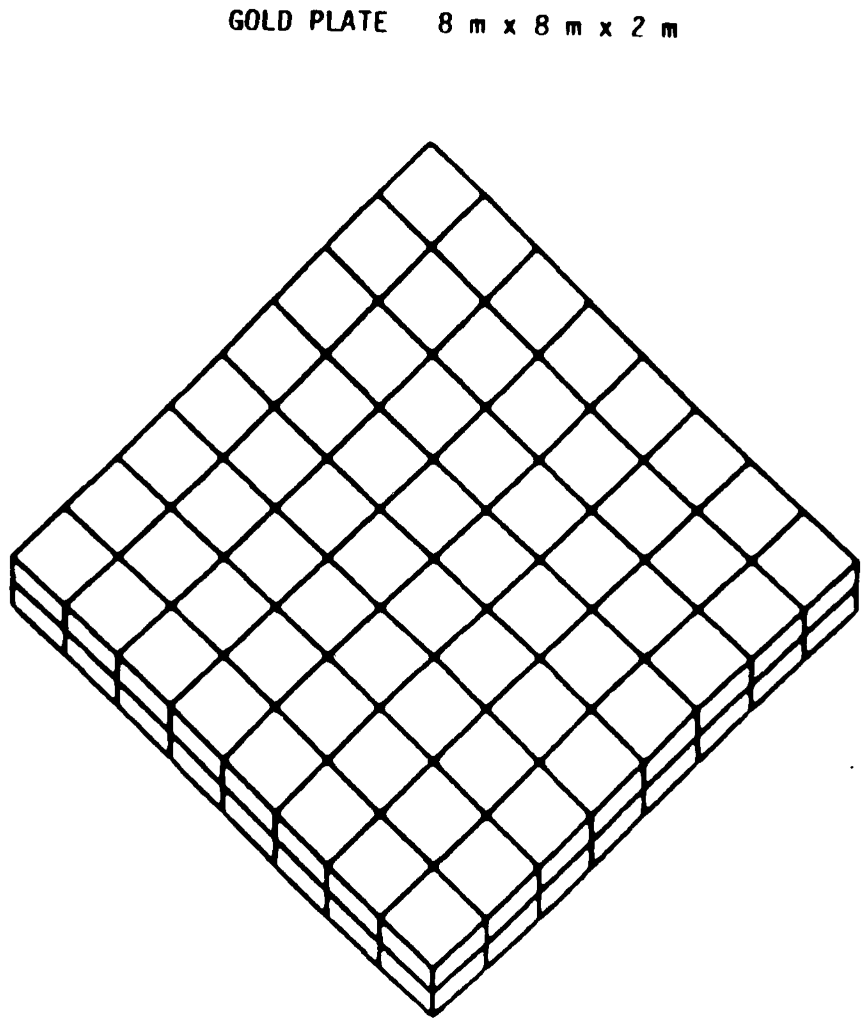
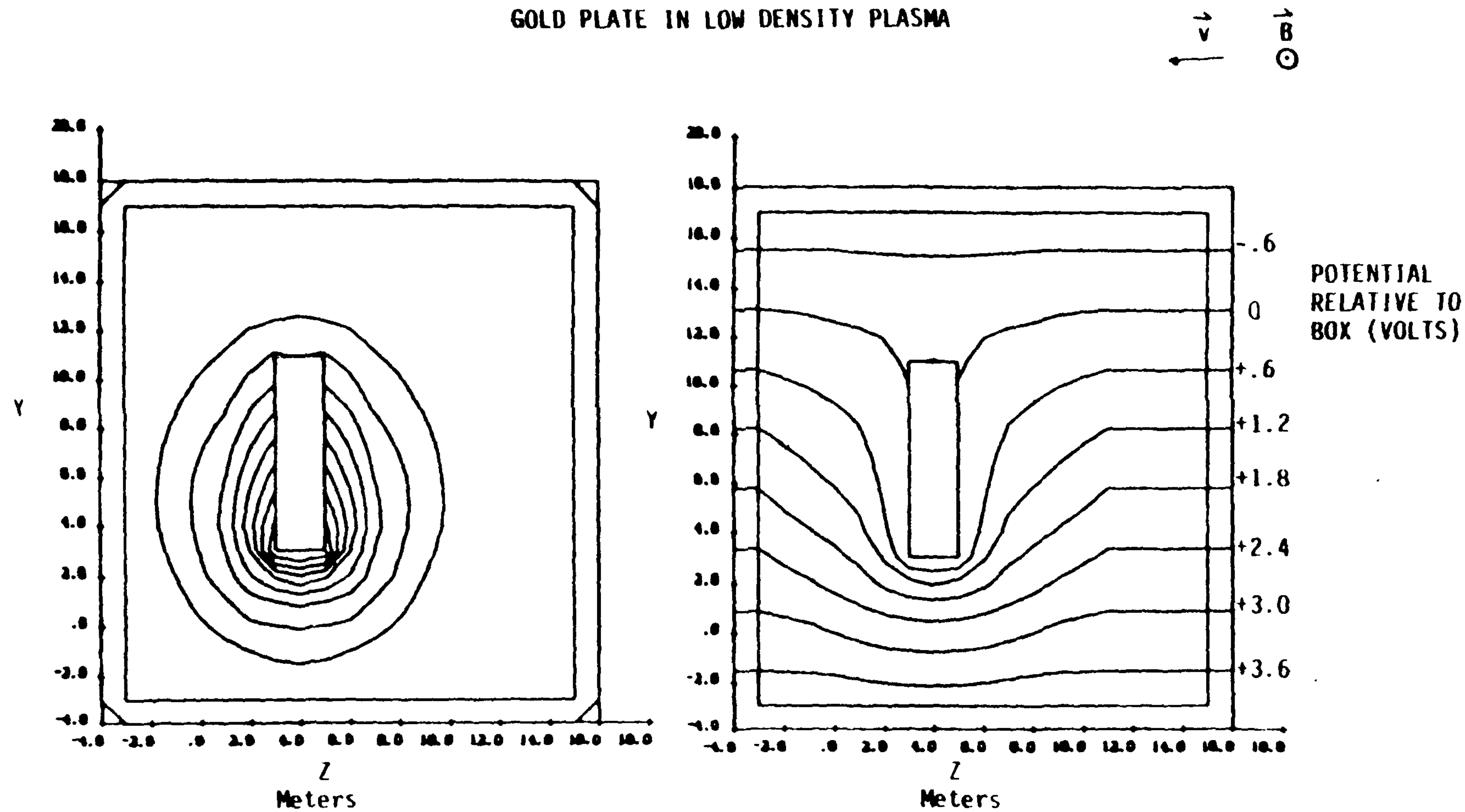


Figure 1. Perspective view of 8 m x 8 m x 2 m gold plate used to generate data for Figures 2 and 3.

GOLD PLATE IN LOW DENSITY PLASMA



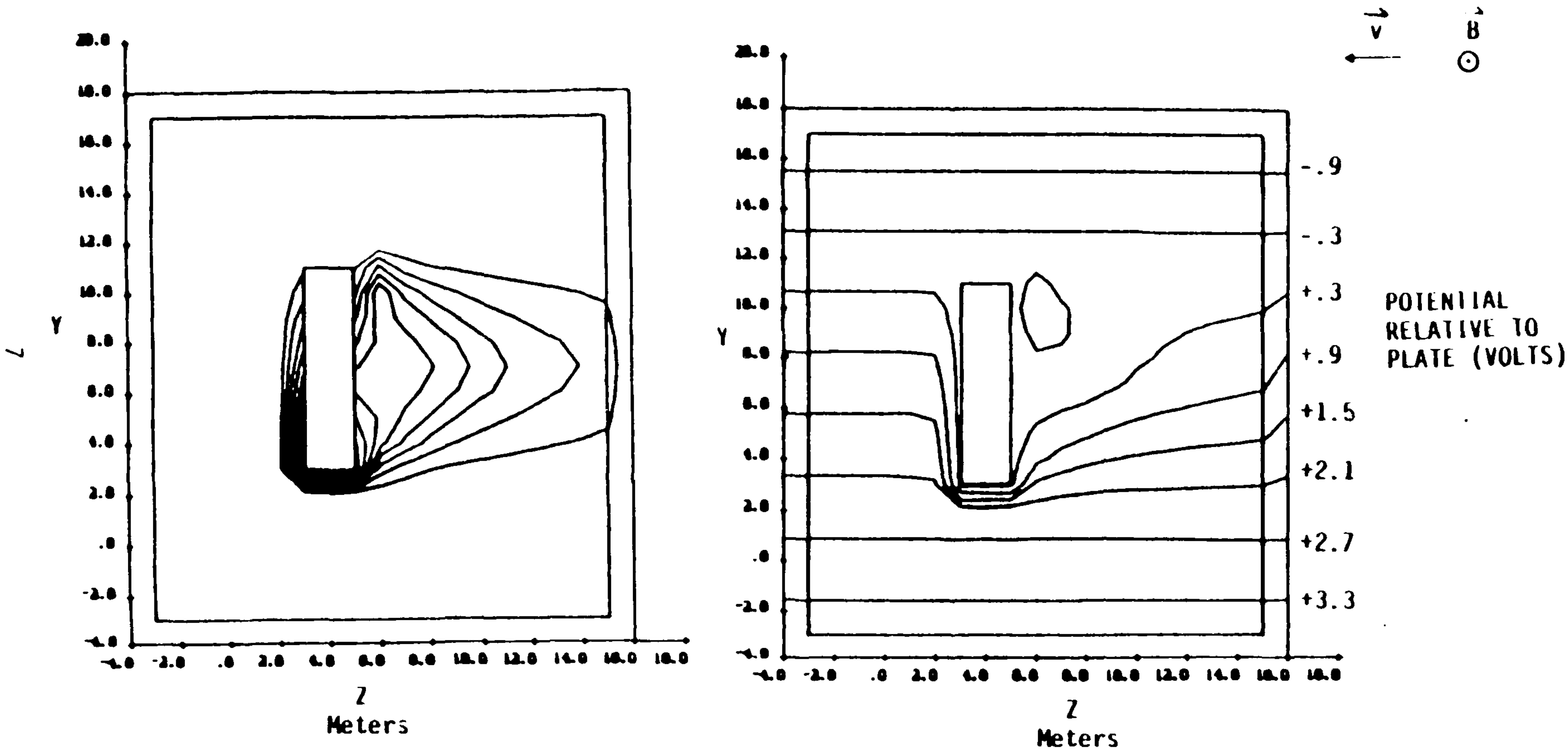
(a) PLASMA REFERENCE FRAME

Vmin = -2.4 V, Vmax = .0 V, dV = .27 V

(b) PLATE'S REFERENCE FRAME

Figure 2. Plate in low density ($1\ m^{-3}$) plasma. No density gradient electric fields.

GOLD PLATE IN HIGH DENSITY PLASMA



(a) PLASMA REFERENCE FRAME

(b) PLATE'S REFERENCE FRAME

Vmin = -2.0 V, Vmax = 0. V, dV = .23 V

Figure 3. Plate in high density (10^{12} m^{-3}) plasma. Both $\vec{v} \times \vec{B}$ and density gradient fields are present in the wake.

GOLD BOX 16 m x 6 m x 2 m

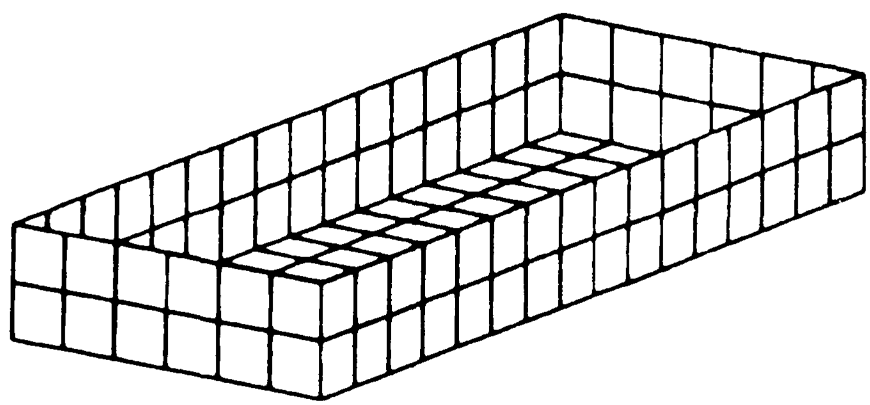
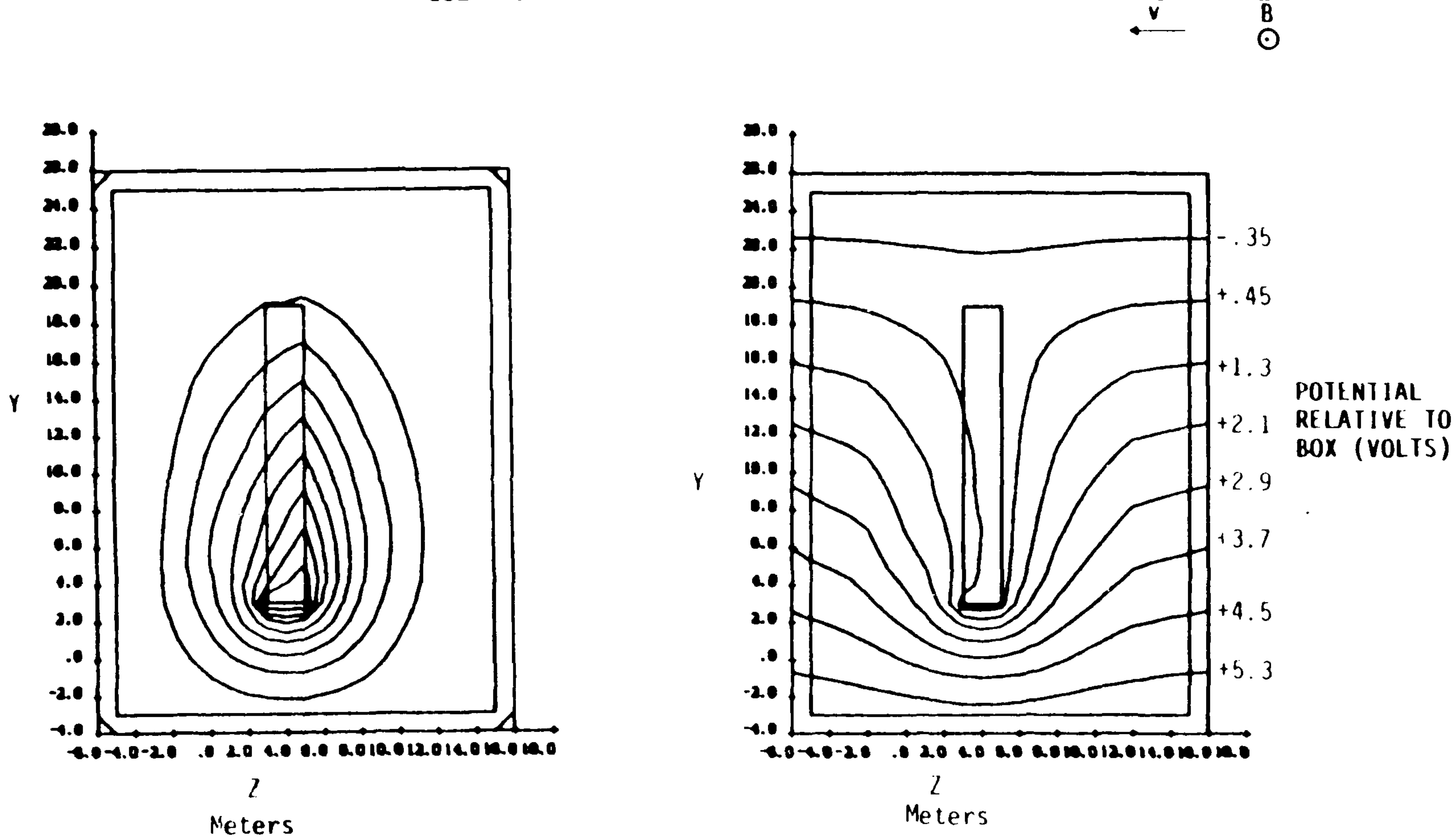


Figure 4. Perspective view of 16 m x 6 m x 2 m gold box useo to generate data for Figures 5 and 6.

GOLD BOX IN LOW DENSITY PLASMA



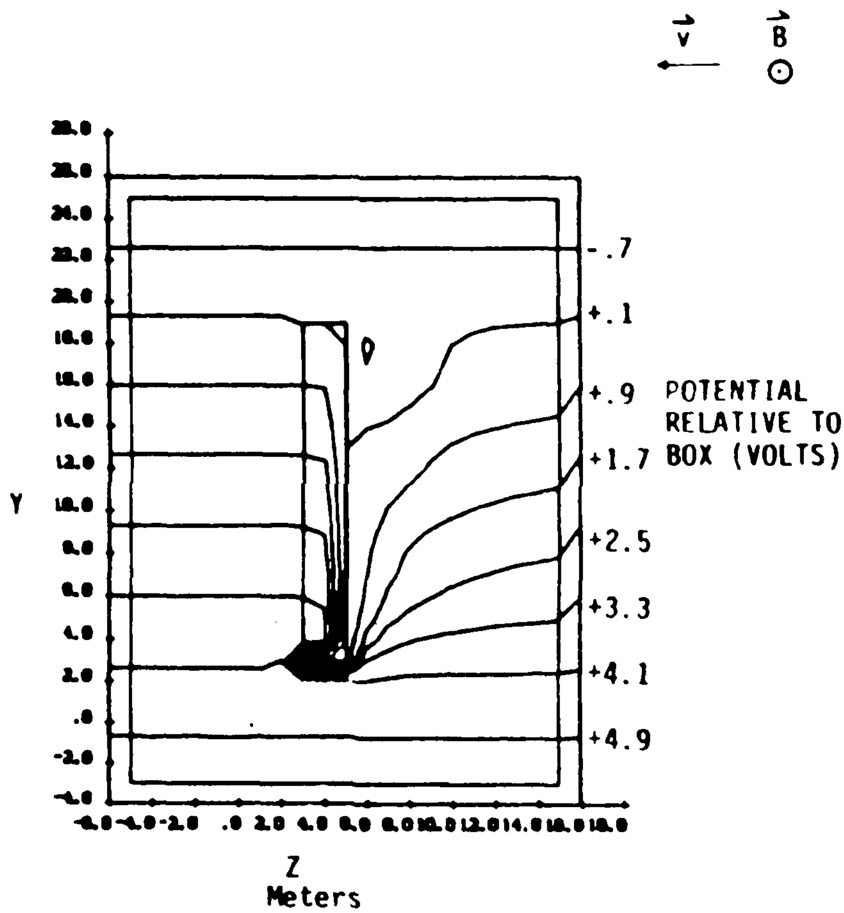
(a) PLASMA REFERENCE FRAME

Vmin = -4.5 V   Vmax = .0 V   dV = .50 V

(b) BOX'S REFERENCE FRAME

Figure 5. Metal box in a low density (1 m^{-3}) plasma. There are density gradient electric fields present.

GOLD BOX IN HIGH DENSITY PLASMA



BOX'S REFERENCE FRAME

Figure 6. Metal box in a high density (10^{12} m^{-3}) plasma with both $\vec{v} \times \vec{B}$ and density gradient electric fields.

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